DEPARTMENT OF PHYSICS

LEVEL II

(15) OFFICE OF NAVAL RESEARCH
Contract N00014-80-C-0213
Project NR 092-558

(14) TR-2

(9) Technical Report No. 2

(6) FRACTO-EMISSION ACCOMPANYING ADHESIVE FAILURE

by

(10) J. T. Dickinson, M. K. Park, E. E. Donaldson and L. C. Jensen

Physics Department
Washington State University
Pullman, WA 99164

(12) 24

(11) Sep[redacted]81

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: Technical Report 2 ✓	2. GOVT ACCESSION NO.: AD-A104 050
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Fracto-Emission Accompanying Adhesive Failure	5. TYPE OF REPORT & PERIOD COVERED: Technical Report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. T. Dickinson, M. K. Park, E. E. Donaldson, and L. C. Jensen	8. CONTRACT OR GRANT NUMBER(s): N00014-80-C-0213 ✓
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Physics Department, Washington State University, Pullman, WA 99164	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 092-558
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Power Program, Arlington, VA 22217	12. REPORT DATE: August 29, 1981
	13. NUMBER OF PAGES: 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Submitted for publication in: Journal of Vacuum Science and Technology

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adhesive failure, interfacial failure, fracture, delamination, crack propagation, fracture surfaces, exo-emission, electron emission, tribostimulated exo-emission, chemi-emission, surface charging, fracture of: polymers, filaments, fibers, composites, filled polybutadiene, elastomers. Peeling of adhesive tape.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental studies of the emission of electrons (EE), positive ions (PIE), and photons (phE) accompanying fracture are presented for systems involving adhesive failure. The systems studied include interfacial failure between epoxy--brittle materials, polybutadiene-glass, and pressure sensitive adhesives--polymers. Time distributions and energy distributions are shown and for a few systems we compare EE and phE.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

FRACTO-EMISSION ACCOMPANYING ADHESIVE FAILURE

J. T. Dickinson, M. K. Park, E. E. Donaldson, and L. C. Jensen

Department of Physics
Washington State University
Pullman, WA 99164

ABSTRACT

For a wide range of materials, emission of electrons (EE), positive ions (PIE), and photons (phE) is observed accompanying fracture. Here we report on work concerning emission from adhesive failure. The systems studied include interfacial failure between epoxy--brittle materials, polybutadiene-glass, and pressure sensitive adhesives--polymers. When interfacial failure occurs, it produces highly excited surfaces with intense charge separation. De-excitation in the presence of surface charge produces intense, long lasting (several minutes) emission. Energy distribution curves for both EE and PIE decrease monotonically with a tail extending out to several hundred eV. For a few systems we compare EE and phE which show different decay characteristics.

INTRODUCTION

During and following the fracture of materials, the emission of charged particles,[1-6] neutral particles,[7] and photons[3,8,9] have been observed. Studies of electron emission (EE) during the tensile elongation of oxide-coated aluminum, sometimes referred to as tribo-stimulated exoemission, have shown that fracture of the oxide coating is the initial cause of the ejected electrons.[4-6] Similarly, positive ion emission (PIE) neutral emission[6] and photon emission[3] have been observed on the same oxide-aluminum systems, and were shown to be due to oxide fracture. (Photon emission is most frequently referred to as triboluminescence.[8,9]) These various types of emission have some shared characteristics suggesting common mechanisms in their production. We refer to all forms of such emission accompanying fracture as "fracto-emission" (FE).

In Ref. 10 we reviewed the factors which appear to contribute to FE and presented a survey of charged particle measurements we made on a wide range of materials undergoing fracture. Briefly, when a crack propagates through a material the crack walls are left in a highly excited, nonequilibrium state. For nonmetals this departure from equilibrium involves broken bonds, liberated fragments (e.g. free radicals, atoms, charged species) defects (e.g. point defects), charge separation often involving the filling of localized surface states and intense electric fields) and a localized rise in temperature. All of these factors represent high concentrations of energy in a small volume and may contribute to fundamental processes such as Auger transitions,[11] ESD-like transitions,[12] and dipole-transitions that lead to FE. An example of this is chemi-emission[13] where during a chemical reaction at a surface an excited intermediate state is produced capable of producing either photons or electrons, the latter by an Auger process (and in our case would involve trapped electrons closest to the vacuum level).

During fracture at interfaces, often called adhesive failure or interfacial failure, the bonds broken and degree of charge separation may be quite

different from cohesive failure in a homogeneous material. For example, Jonath[14] discusses the fact that as one approaches the adherend, there is a gradient in chemical and mechanical structure due to an influence of the bonding surface. Thus, upon failure, depending upon the locus of fracture, unique excitations and species can be produced. Also, in polymers, it is known that fracture can produce high concentrations of free radicals, as determined by e.s.r. measurements.[15]

In this paper we present additional work on FE accompanying and following the fracture of materials where interfacial failure occurs for systems involving a polymeric component (e.g. matrix, adhesive, or adherend).

EXPERIMENTAL

Details of our experimental procedures are given in Ref. 10. The samples are fractured by applying tensile stress. The typical cross-sections of bulk samples were 0.1 to 20 mm^2. We fractured bare filaments, typically 10 μm in diameter, of such materials as glass and Kevlar. These were mounted so that single filaments could be broken sequentially. Epoxy-strands of these materials consisted of about 250 filaments in DOW DER 332 Epoxy.

Filled elastomers consisted of untreated small glass beads 30-95 μm in diameter in a polybutadiene matrix. These samples had cross-sections of 15 mm^2 and contained amounts of glass beads varying from 0 to 34% by volume.

Another type of interfacial failure studied involved the delamination of 3M Filament Tape; i.e., the separation of the polyester backing from the glass filaments which adhere by means of a natural rubber-based adhesive. For such studies, typically 1 cm^2 of surface was created in a time of 10 s. Similar studies were made from the peeling of 3M MAGIC TRANSPARENT TAPE from a PMMA surface.

The charged particle experiments were carried out at 1-4 x 10^{-6} Torr and the residual gases consisted primarily of CO, H_2, and CO_2. Some samples were tested in an ion-pumped system at 10^{-8} Torr--no differences in the FE were

observed in the two environments. Charged particles were detected with channel electron multipliers (CEM), Galileo Electro-Optics (4039), positioned 1 cm from the sample. Photons were detected using a Bendix BX 754A Photon Countertube with an S-20 photo-sensitive surface. Data were handled with standard pulse counting methods and stored in a multichannel analyzer.

RESULTS

The fracture of filaments of graphite and Kevlar gave rapidly decaying EE with time constants on the order of 10 μs for graphite and 100 μs for Kevlar. The graphite decay is very similar to that observed for E-Glass and S-Glass filaments.[10] We also fractured pure DER 332 epoxy and obtained the 25 μs decay time as shown in Fig. 1. PIE time distributions for these materials are indistinguishable from these electron curves.

When we fracture the corresponding fiber-reinforced epoxy strands made from the same filaments and epoxy, we find emission curves that differ from those for pure materials. Figure 2 shows EE and PIE curves for the Kevlar-Epoxy and Graphite-Epoxy systems. On the scale shown, the time required for fracture is usually less than one channel. The decay is seen to last for many seconds--some of the more intense emitters will give detectable emission an hour after fracture. Although intensities differ, we have simultaneously measured PIE and EE from the same fracture event and found the decay curves to be of the same shape. This suggests a common rate-limiting step for the two types of emission. SEM photographs of the samples show delamination and separation of the filaments from the epoxy. This interfacial or adhesive failure is most likely responsible for these major FE components with the slow decay and may serve as an indicator of the extent of interfacial failure that has occurred. Figure 3 shows on a log scale the normalized energy distribution of the EE and PIE produced by differentiation of retarding potential curves. Both curves are very similar showing a peak near 0 eV with a significant quantity of higher

energy particles in the tail. The presence of these higher energy particles suggests that the charging of the fracture surface (due to separation of charges) plays an important role in producing the observed charged FE. Again, the similarities in the EE and PIE energy distributions provides further support that they share a common mechanistic step.

Similar results are seen for polybutadiene with and without glass beads as seen in Fig. 4. The peak intensity created during fracture and the after-emission are considerably more intense when the glass beads are present. Gent[16] has shown that the beads become detached during straining of the matrix. This adhesive failure is considered the cause of the enhanced FE. Figure 5 shows the dependence of the total emission (in 200 s) as a function of the quantity of glass beads in the polybutadiene, for both EE and PIE increasing with increasing bead concentration.

The peeling of tape from a surface also produces charged particle emission as well as visible photons. Figure 6 shows the EE and phE from peeling 3M MAGIC TRANSPARENT TAPE from Plexiglas. The EE is high during peeling and decays slowly afterwards. The phE is above the noise only during peelings. Although these FE components may share a common excitation step, the photon mechanism decays away much quicker. Similar results are seen for the delamination of the filaments from the polyester backing of 3M FILAMENT TAPE, as seen in Fig. 7. Between a and b we have delaminated the surfaces, and reattached the surfaces at c (which causes the EE to disappear), then repeated the process, showing that EE and phE is produced by the second and third detachment (i.e., virgin bonds are not necessary).

CONCLUSIONS

We have shown that fracture involving adhesive failure leads to intense, long-lasting EE and PIE. This has been shown for fiber-reinforced epoxy, polybutadiene filled with glass beads, and pressure sensitive adhesives. The

detachment of adhesives from adherends is frequently accompanied by intense charge separation[14] as well as the creation of excited and reactive species, e.g., free radicals. As previously argued,[10] we do not attribute the observed charged particle emission to field emission, but we do feel that the electric field from surface charge patches (of both signs) is responsible for the particle kinetic energies observed and may also affect the emission intensity. The latter could be due to an influence on the mobility of active species near or at the fracture surface as well as a possible E-field dependence of transition probabilities in excited species. The enhanced effects we see when interfaces are involved is likely due to a) the different types of chemical species produced by adhesive failure (as compared to cohesive failure) and b) the degree of charging that occurs with interfacial failure.

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research, Contract N0014-80-C-0213.

We wish to thank R. L. Moore, Lawrence Livermore Laboratory, for providing samples of filaments and fiber/epoxy strands, and Dr. A. N. Gent, University of Akron Institute of Polymer Science for supplying the polybutadiene samples. We are also grateful for their interest and advice.

Figure Captions

Fig. 1. Time distributions of EE due to fracture of 10 μm graphite and Kevlar filaments and bulk epoxy (Dow DER 332).
Fig. 2. EE and PIE from fracture of filament/epoxy strands: Kevlar and graphite.
Fig. 3. Energy distributions, on a log scale, for EE and PIE from Kevlar/Epoxy.
Fig. 4. EE and PIE from fracture of polybutadiene with and without glass beads.
Fig. 5. The total emission (counts accumulated over 200 s) as a function of the volume percent of glass beads in polybutadiene.
Fig. 6. EE and Photons from peeling 3M-MAGIC TRANSPARENT TAPE from PMMA.
Fig. 7. EE and Photons from Delamination of 3M FILAMENT TAPE.

References

1. J. T. Dickinson, P. F. Bräunlich, L. Larson, and A. Marceau, Appl. Surf. Sci. 1, 515 (1978).
2. D. L. Doering, T. Oda, J. T. Dickinson, and P. F. Bräunlich, Appl. Surf. Sci. 3, 196 (1979).
3. B. Z. Rosenblum, P. F. Bräunlich, and L. Himmel, J. Appl. Phys. 48, 5262 (1977).
4. J. T. Dickinson, D. B. Snyder, and E. E. Donaldson, J. Vac. Sci. Technol. 17, 429 (1980).
5. J. T. Dickinson, D. B. Snyder, and E. E. Donaldson, Thin Solid Films 72, 223, (1980).
6. J. T. Dickinson, E. E. Donaldson, and D. B. Snyder, J. Vac. Sci. Technol. 18, 238 (1981).
7. L. A. Larson, J. T. Dickinson, P. F. Bräunlich, and D. B. Snyder, J. Vac. Sci. Technol. 16, 590 (1979).
8. A. J. Walton, Adv. Phys. 26, 887 (1977).
9. J. I. Zink, Acc. Chem. Res. 11, 289 (1978).
10. J. T. Dickinson, E. E. Donaldson, and M. K. Park, J. Mat. Sci., to be published.
11. H. Hagstrum in Experimental Methods in Catalytic Research Vol. III, R. B. Anderson and P. T. Dawson, ed. (New York, Academic Press, 1976), pp. 42-81.
12. M. L. Knotek and P. J. Feibelman, Phys. Rev. Letters 40, 964 (1978).
13. B. Kesemo, E. Tornqvist, J. K. N. Ørskov, and B. I. Lundqvist, Surf. Sci. 89, 554 (1979).
14. A. D. Jonath in Adhesion and Adsorption of Polymers, Part A, L. H. Lee, ed. (New York, Plenum Press), pp. 175-193.
15. E. H. Andrews, in The Physics of Glassy Polymers, R. N. Haward, ed. (New York, John Wiley), pp. 447-451.
16. A. N. Gent, private communication.
17. B. V. Deryagin, N. A. Krotova, and V. P. Smilga, Adhesion of Solids (English Translation) Consultants Bureau, New York, 1978.

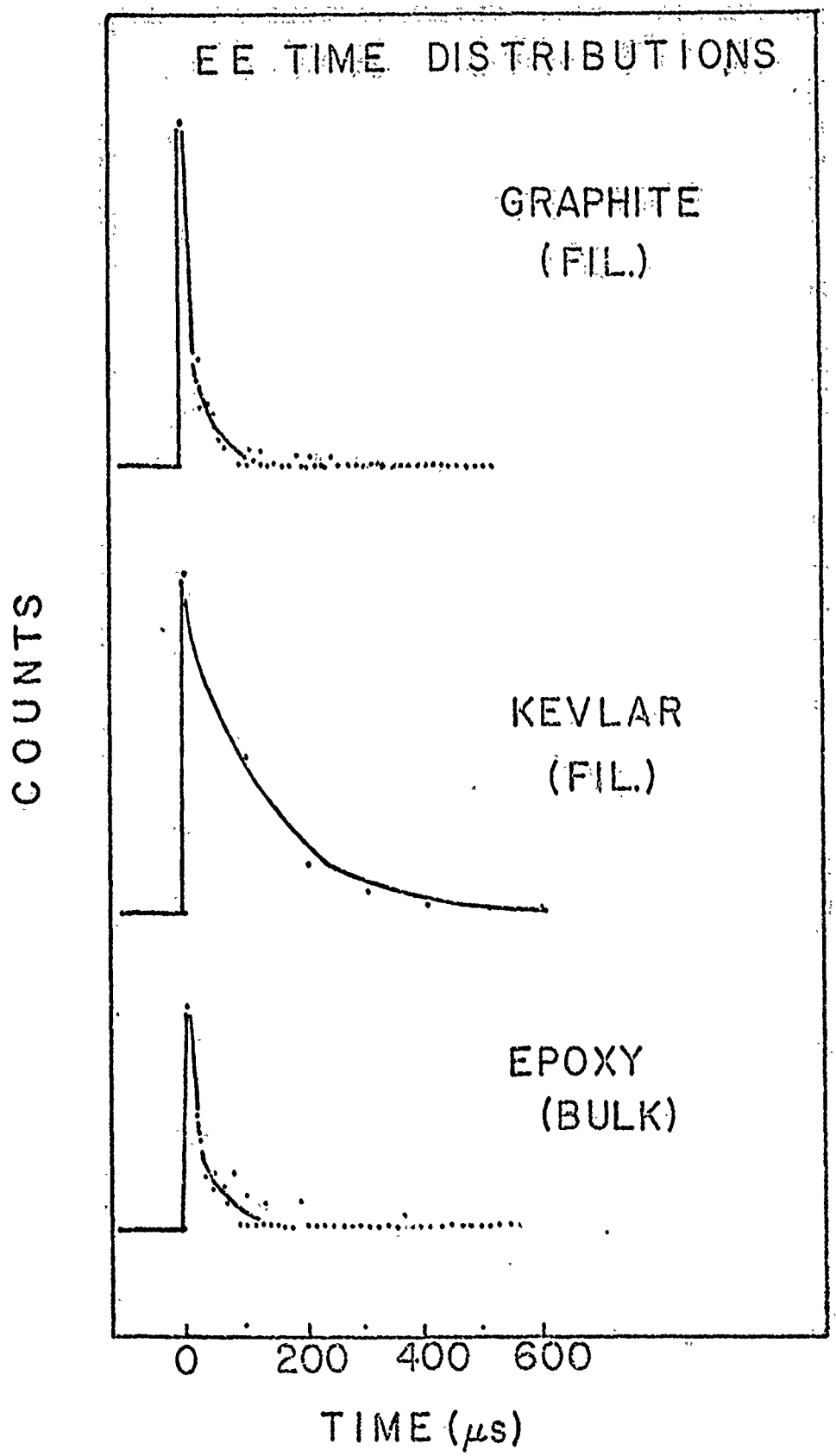
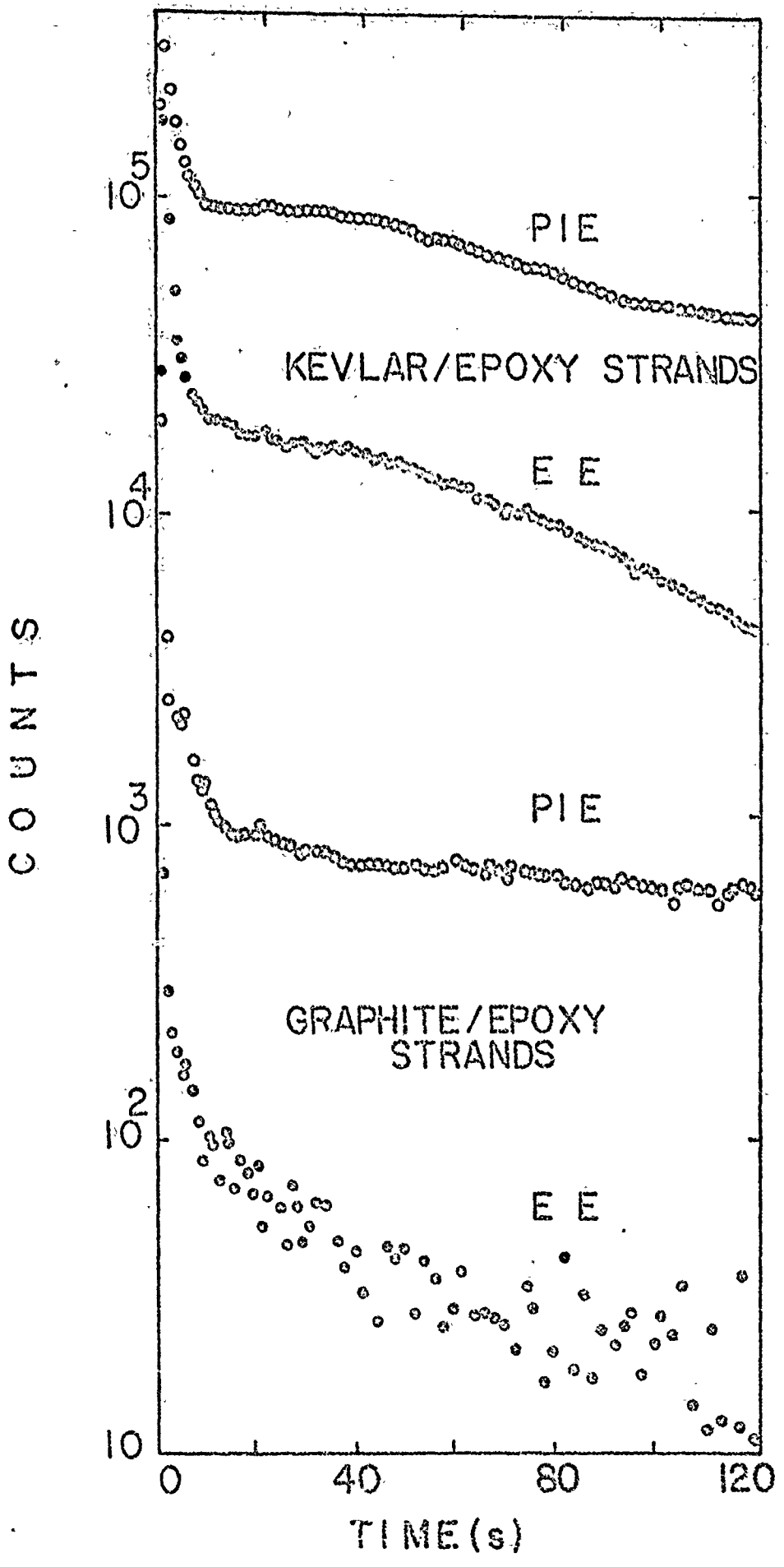

EE TIME DISTRIBUTIONS
GRAPHITE
(FIL.)
KEVLAR
(FIL.)
EPOXY
(BULK)
COUNTS
0
200
400
600
TIME (μs)

Fig. 1


COUNTS
10^5
10^4
10^3
10^2
10
PIE
KEVLAR/EPOXY STRANDS
E E
PIE
GRAPHITE/EPOXY
STRANDS
E E
0
40
80
120
TIME (s)

EE AND PIE ENERGY DISTRIBUTIONS
FROM KEVLAR-EPOXY STRANDS

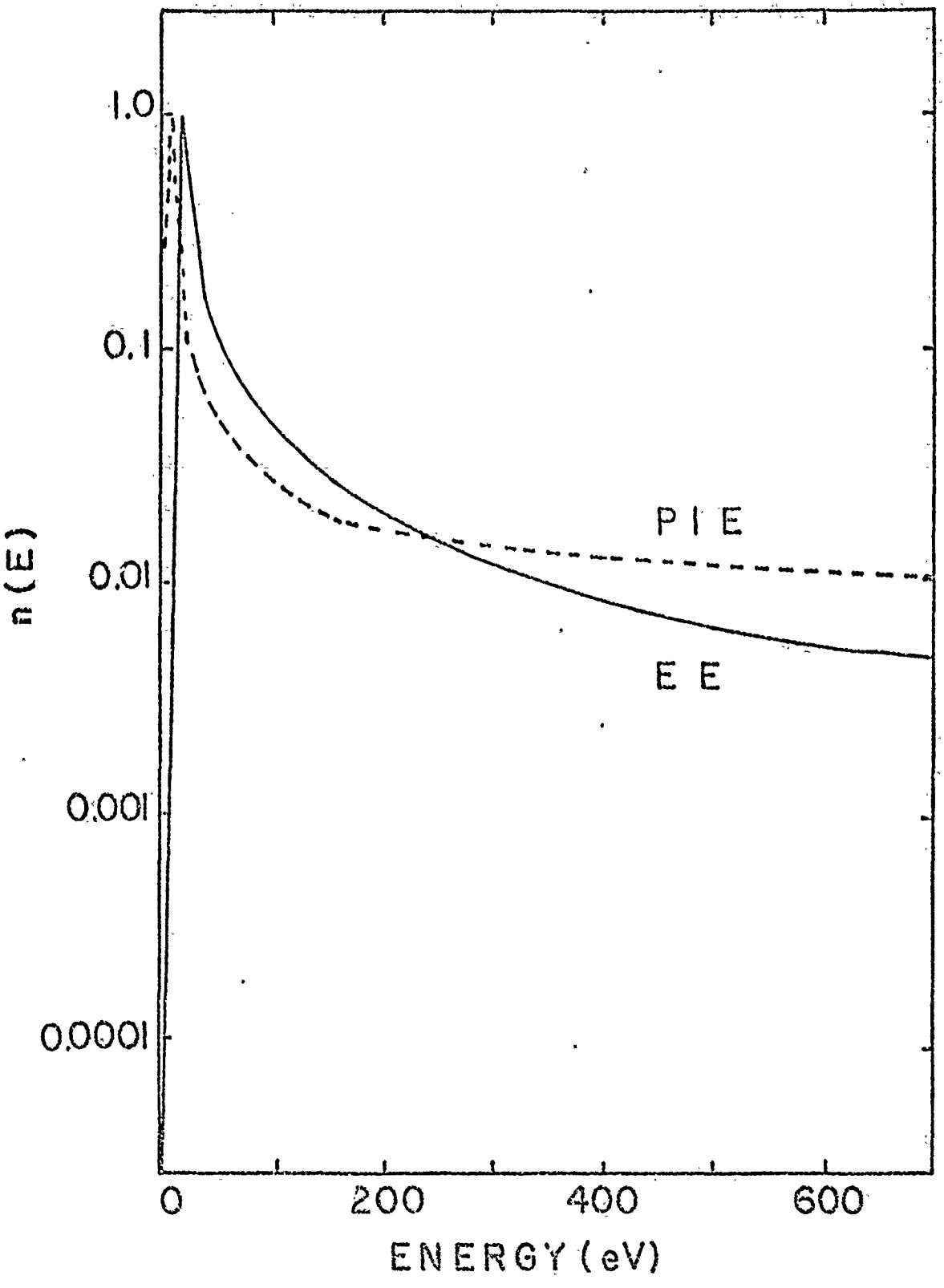


Fig. 3

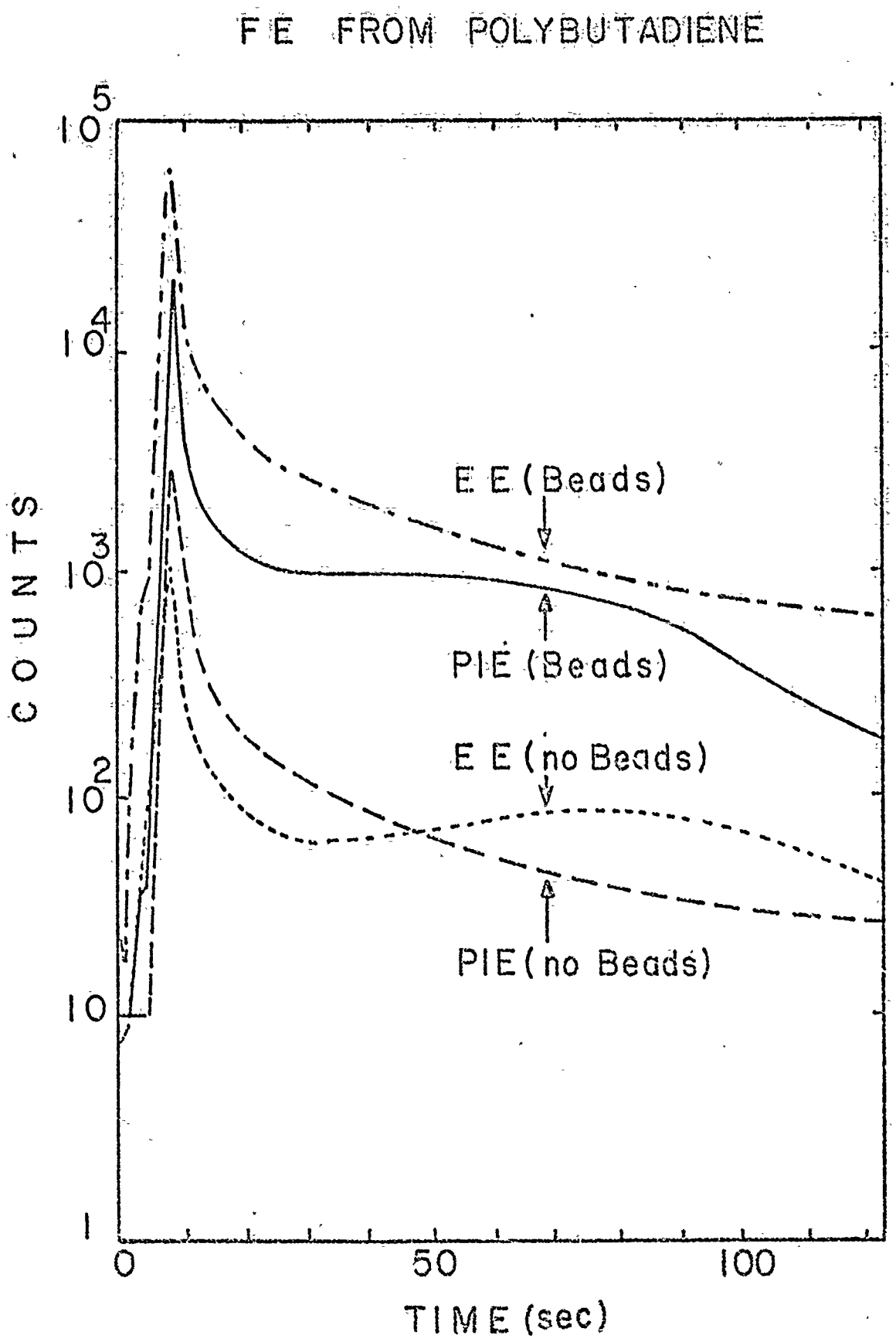
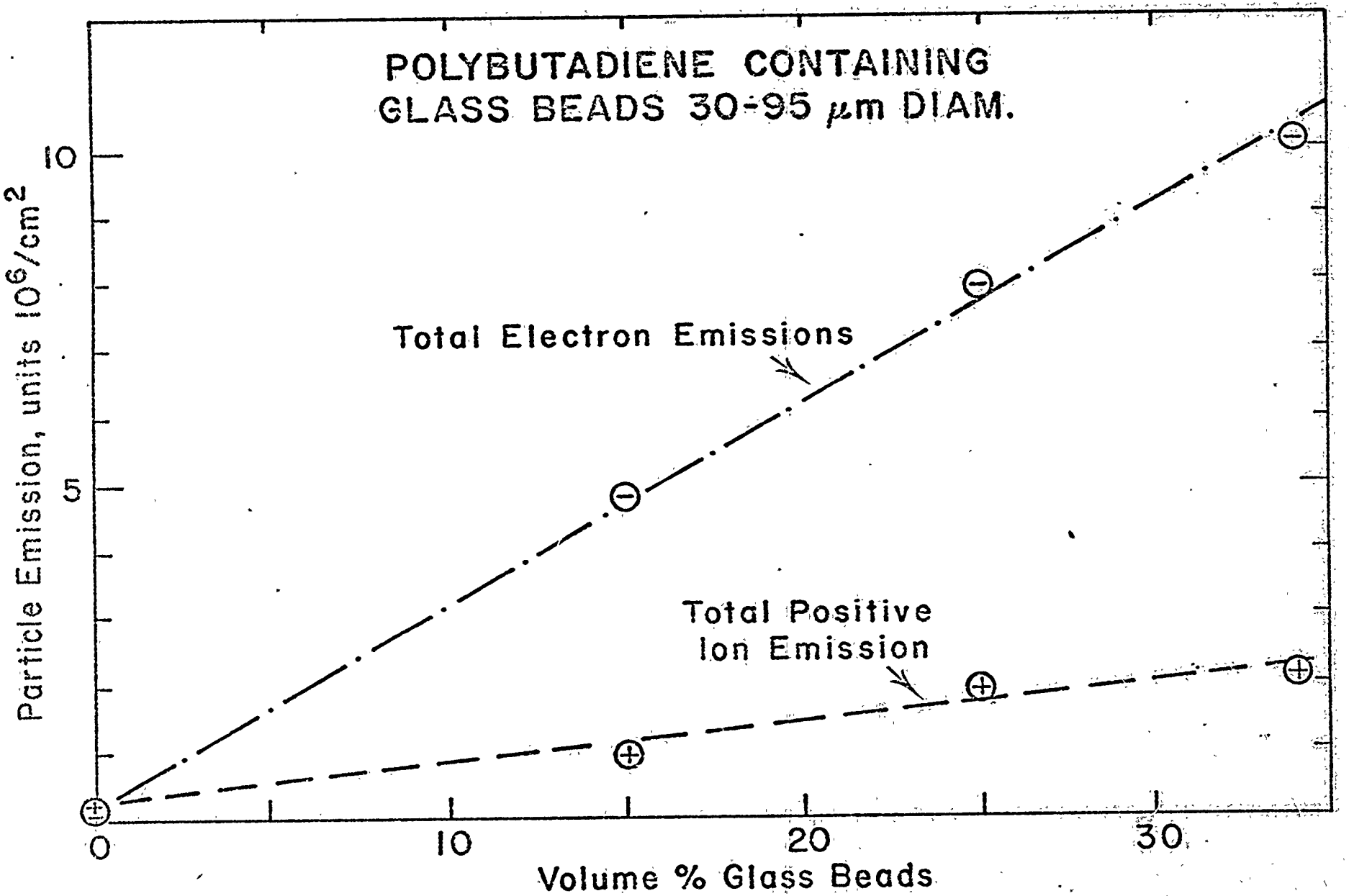
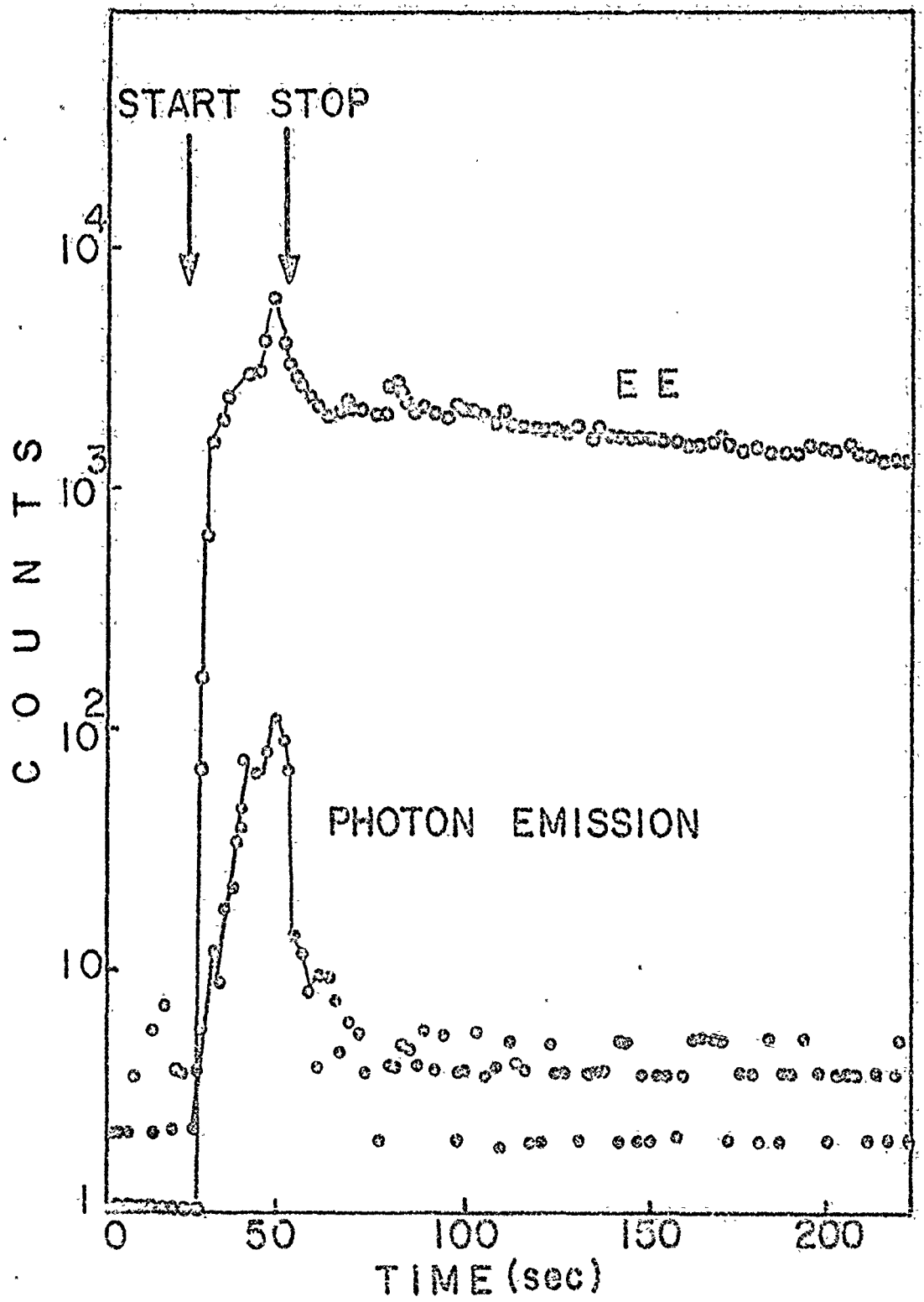

FE FROM POLYBUTADIENE
COUNTS
10^5
10^4
10^3
10^2
10
1
EE (Beads)
PIE (Beads)
EE (no Beads)
PIE (no Beads)
0
50
100
TIME (sec)

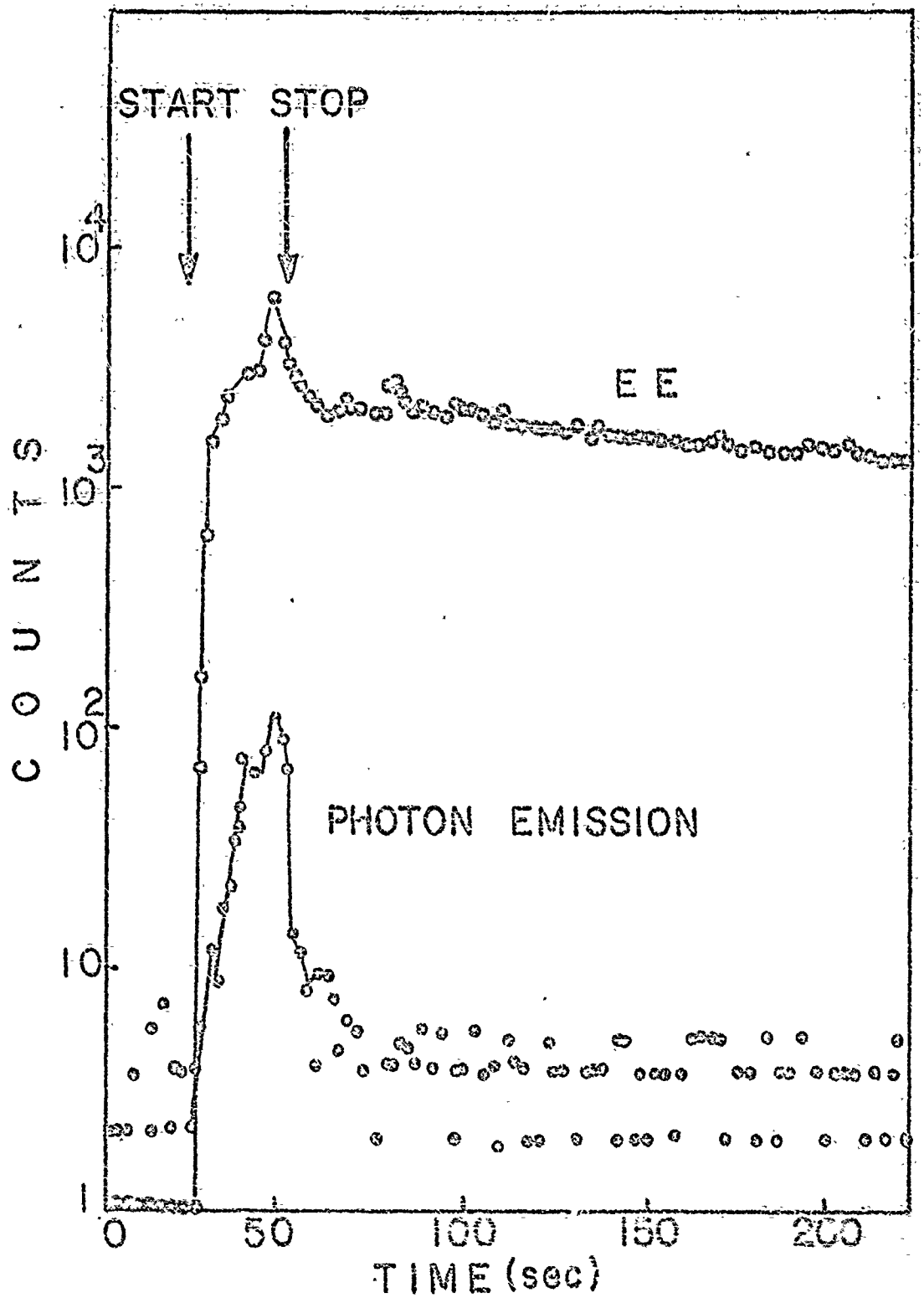
Fig 4


POLYBUTADIENE CONTAINING
GLASS BEADS 30-95 μm DIAM.
Particle Emission, units $10^6/cm^2$
10
5
0
10
20
30
Volume % Glass Beads
Total Electron Emissions
Total Positive
Ion Emission

EE AND PHOTON EMISSION FROM
PEELING 3M-MAGIC TAPE FROM PMMA



EE AND PHOTON EMISSION FROM PEELING 3M-MAGIC TAPE FROM PMMA



DISTRIBUTION LIST

	No. Copies	No. Copies
Dr. S. Sheffield Sandia Laboratories Division 2513 P.O. Box 5800 Albuquerque, NM 87185	1	
Dr. M. Farber Space Sciences, Inc. 135 Maple Avenue Monrovia, CA 91016	1	
Dr. Y. M. Gupta SRI International 333 Ravenswood AVenue Menlo Park, CA 94025	1	
Mr. M. Hill SRI International 333 Ravenswood Avenue Menlo Park, CA 94025	1	
Professor Richard A. Schapery Texas A&M Univ. Dept of Civil Engineering College Station, TX 77843	1	
Dr. Stephen Swanson Univ. of Utah Dept. of Mech. & Industrial Engineering MEB 3008 Salt Lake City, UT 84112	1	
Mr. J. D. Byrd Thiokol Corp. Huntsville Huntsville Div. Huntsville, AL 35807	1	
Professor G. D. Duvall Washington State University Dept. of Physics Pullman, WA 99163	1	
Prof. T. Dickinson Washington State University Dept. of Physics Pullman, WA 99163	1	

DYN

DISTRIBUTION LIST

	No. Copies
Dr. Ingo W. May Army Ballistic Research Labs ARRADCOM Code DRDAR-BLI Aberdeen Proving Ground, MD 21005	1
Professor N.W. Tschoegl California Institute of Tech Dept. of Chemical Engineering Pasadena, CA 91125	1
Professor M.D. Nicol University of California Dept. of Chemistry 405 Hilgard Avenue Los Angeles, CA 90024	1
Professor A. G. Evans University of California Berkeley, CA 94720	1
Professor T. Litovitz Catholic Univ. of America Physics Department 520 Michigan Ave., N.E. Washington, D.C. 20017	1
Professor W. G. Knauss Graduate Aeronautical Lab California Institute of Tech. Pasadena, CA 91125	1
Professor Edward Price Georgia Institute of Tech. School of Aerospace Engin. Atlanta, Georgia 30332	1
Dr. Kenneth O. Hartman Hercules Aerospace Division Hercules Incorporated P.O. Box 210 Cumberland, MD 21502	1
Dr. Thor L. Smith IBM Research Lab D42.282 San Jose, CA 95193	1
Dr. J. P. Marshall Dept. 52-35, Bldg. 204/2 Lockheed Missile & Space Co. 3251 Hanover Street Palo Alto, CA 94304	1
Ms. Joan L. Janney Los Alamos National Lab Mail Stop 920 Los Alamos, NM 87545	1
Dr. J. M. Walsh Los Alamos Scientific Lab Los Alamos, NM 87545	1
Professor R. W. Armstrong Univ. of Maryland Department of Mechanical Eng. College Park, MD 20742	1
Prof. Richard A. Reinhardt Naval Postgraduate School Physics & Chemistry Dept. Monterey, CA 93940	1
Dr. R. Bernecker Naval Surface Weapons Center Code R13 White Oak, Silver Spring, MD 20910	1
Dr. M. J. Kamlet Naval Surface Weapons Center Code R11 White Oak, Silver Spring, MD 20910	1
Professor J. D. Achenbach Northwestern University Dept. of Civil Engineering Evanston, IL 60201	1
Dr. N. L. Basdekas Office of Naval Research Mechanics Program, Code 432 Arlington, VA 22217	1
Professor Kenneth Kuo Pennsylvania State Univ. Dept. of Mechanical Engineering University Park, PA 16802	1

DISTRIBUTION LIST

	No. Copies
Dr. J.F. Kincaid Strategic Systems Project Office Department of the Navy Room 901 Washington, D.C. 20376	1
Strategic Systems Project Office Propulsion Unit Code SP2731 Department of the Navy Washington, D.C. 20376	1
Mr. E.L. Throckmorton Strategic Systems Project Office Department of the Navy Room 1048 Washington, D.C. 20376	1
Dr. D.A. Flanigan Thiokol Huntsville Division Huntsville, Alabama 35807	1
Mr. G.F. Mangum Thiokol Corporation Huntsville Division Huntsville, Alabama 35807	1
Mr. E.S. Sutton Thiokol Corporation Elkton Division P.O. Box 241 Elkton, MD 21921	1
Dr. G. Thompson Thiokol Wasatch Division MS 240 P.O. Box 524 Brigham City, UT 84302	1
Dr. T.F. Davidson Technical Director Thiokol Corporation Government Systems Group P.O. Box 9258 Ogden, Utah 84409	1
Dr. C.W. Vriesen Thiokol Elkton Division P.O. Box 241 Elkton, MD 21921	1
Dr. J.C. Hinshaw Thiokol Wasatch Division P.O. Box 524 Brigham City, Utah 84302	1
U.S. Army Research Office Chemical & Biological Sciences Division P.O. Box 12211 Research Triangle Park NC 27709	1
Dr. R.F. Walker USA ARRADCOM DRDAR-LCE Dover, NJ 07801	1
Dr. T. Sinden Munitions Directorate Propellants and Explosives Defence Equipment Staff British Embassy 3100 Massachusetts Ave. Washington, D.C. 20008	1
LTC B. Loving AFROL/LK Edwards AFB, CA 93523	1
Professor Alan N. Gent Institute of Polymer Science University of Akron Akron, OH 44325	1
Mr. J. M. Frankle Army Ballistic Research Labs ARRADCOM Code DRDAR-BLI Aberdeen Proving Ground, MD 21005	1

DISTRIBUTION LIST

	No. Copies
Mr. J. Murrin Naval Sea Systems Command Code 62R2 Washington, D.C. 20362	1
Dr. D.J. Pastine Naval Surface Weapons Cneter Code R04 White Oak Silver Spring, MD 20910	1
Mr. L. Roslund Naval Surface Weapons Center Code R122 White Oak, Silver Spring MD 20910	1
Mr. M. Stosz Naval Surface Weapons Center Code R121 White Oak Silver Spring, MD 20910	1
Dr. E. Zimmet Naval Surface Weapons Center Code R13 White Oak Silver Spring, MD 20910	1
Dr. D. R. Derr Naval Weapons Center Code 388 China Lake, CA 93555	1
Mr. Lee N. Gilbert Naval Weapons Center Code 3205 China Lake, CA 93555	1
Dr. E. Martin Naval Weapons Center Code 3858 China Lake, CA 93555	1
Mr. R. McCartan Naval Weapons Center Code 3272 China Lake, CA 93555	1
Dr. A. Nielsen Naval Weapons Center Code 385 China Lake, CA 93555	1
Dr. R. Reed, Jr. Naval Weapons Center Code 388 China Lake, CA 93555	1
Dr. L. Smith Naval Weapons Center Code 3205 China Lake, CA 93555	1
Dr. B. Douda Naval Weapons Support Center Code 5042 Crane, Indiana 47522	1
Dr. A. Faulstich Chief of Naval Technology MAT Code 0716 Washington, D.C. 20360	1
LCDR J. Walker Chief of Naval Material Office of Naval Technology MAT, Code 0712 Washington, D.C. 20360	1
Mr. Joe McCartney Naval Ocean Systems Center San Diego, CA 92152	1
Dr. S. Yamamoto Marine Sciences Division Naval Ocean Systems Center San Diego, CA 91232	1
Dr. G. Bosmajian Applied Chemistry Division Naval Ship Research & Development Center Annapolis, MD 21401	1
Dr. H. Shuey Rohn and Haas Company Huntsville, Alabama 35801	1

DISTRIBUTION LIST

	No. Copies
Mr. R. Brown Naval Air Systems Command Code 330 Washington, D.C. 20361	1
Dr. H. Rosenwasser Naval Air Systems Command AIR-310C Washington, D.C. 20360	1
Mr. B. Sobers Naval Air Systems Command Code 03P25 Washington, D.C. 20360	1
Dr. L.R. Rothstein Assistant Director Naval Explosives Dev. Engineering Dept. Naval Weapons Station Yorktown, VA 23691	1
Dr. Lionel Dickinson Naval Explosive Ordnance Disposal Tech. Center Code D Indian Head, MD 20640	1
Mr. C.L. Adams Naval Ordnance Station Code PM4 Indian Head, MD 20640	1
Mr. S. Mitchell Naval Ordnance Station Code 5253 Indian Head, MD 20640	1
Dr. William Tolles Dean of Research Naval Postgraduate School Monterey, CA 93940	1
Naval Research Lab. Code 6100 Washington, D.C. 20375	1
Dr. J. Schnur Naval Research Lab. Code 6510 Washington, D.C. 20375	1
Mr. R. Beauregard Naval Sea Systems Command SEA 64E Washington, D.C. 20362	1
Mr. G. Edwards Naval Sea Systems Command Code 62R3 Washington, D.C. 20362	1
Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, PA 19112	1
Dr. H.G. Adolph Naval Surface Weapons Center Code R11 White Oak Silver Spring, MD 20910	1
Dr. T.D. Austin Naval Surface Weapons Center Code R16 Indian Head, MD 20640	1
Dr. T. Hall Code R-11 Naval Surface Weapons Center White Oak Laboratory Silver Spring, MD 20910	1
Mr. G.L. Mackenzie Naval Surface Weapons Center Code R101 Indian Head, MD 20640	1
Dr. K.F. Mueller Naval Surface Weapons Center Code R11 White Oak Silver Spring, MD 20910	1

DISTRIBUTION LIST

	No. Copies
Dr. R.G. Rhoades Commander Army Missile Command DRSMI-R Redstone Arsenal, AL 35898	1
Dr. W.D. Stephens Atlantic Research Corp. Pine Ridge Plant 7511 Wellington Rd. Gainesville, VA 22065	1
Dr. A.W. Barrows Ballistic Research Laboratory USA ARRADCOM DRDAR-BLP Aberdeen Proving Ground, MD 21005	1
Dr. C.M. Frey Chemical Systems Division P.O. Box 358 Sunnyvale, CA 94086	1
Professor F. Rodriguez Cornell University School of Chemical Engineering Olin Hall, Ithaca, N.Y. 14853	1
Defense Technical Information Center DTIC-DDA-2 Cameron Station Alexandria, VA 22314	12
Dr. Rocco C. Musso Hercules Aerospace Division Hercules Incorporated Alleghany Ballistic Lab P.O. Box 210 Washington, D.C. 21502	1
Dr. Ronald L. Simmons Hercules Inc. Eglin AFATL/DLDL Eglin AFB, FL 32542	1
Dr. E.H. Debutts Hercules Inc. Baccus Works P.O. Box 98 Magna, UT 84044	1
Dr. James H. Thacher Hercules Inc. Magna Baccus Works P.O. Box 98 Magna, UT 84044	1
Mr. Theordore M. Gilliland Johns Hopkins University APL Chemical Propulsion Info. Agency Johns Hopkins Road Laurel, MD 20810	1
Dr. R. McGuire Lawrence Livermore Laboratory University of California Code L-324 Livermore, CA 94550	1
Dr. Jack Linsk Lockheed Missiles & Space Co. P.O. Box 504 Code Org. 83-10, Bldg. 154 Sunnyvale, CA 94088	1
Dr. B.G. Craig Los Alamos National Lab P.O. Box 1663 NSP/DOD, MS-245 Los Alamos, NM 87545	1
Dr. R.L. Rabie WX-2, MS-952 Los Alamos National Lab. P.O. Box 1663 Los Alamos NM 37545	1
Dr. P. Rogers, WX-2 Los Alamos Scientific Lab. P.O. Box 1663 Los Alamos, NM 87545	1

DISTRIBUTION LIST

	No. Copies
Dr. L.V. Schmidt Assistant Secretary of the Navy (R,E, and S) Room 5E 731 Pentagon Washington, D.C. 20350	1
Dr. A.L. Slafkosky Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Dr. Richard S. Miller Office of Naval Research Code 413 Arlington, VA 22217	10
Mr. David Siegel Office of Naval Research Code 260 Arlington, VA 22217	1
Dr. R.J. Marcus Office of Naval Research Western Office 1030 East Green Street Pasadena, CA 91106	1
Dr. Larry Peebles Office of Naval Research East Central Regional Office 666 Summer Street, Bldg. 114-D Boston, MA 02210	1
Dr. Phillip A. Miller Office of Naval Research San Francisco Area Office One Hallidie Plaza, Suite 601 San Francisco, CA 94102	1
Mr. Otto K. Heiney AFATL - DLDL Elgin AFB, FL 32542	1
Mr. R. Geisler ATTN: MKP/MS24 AFRPL Edwards AFB, CA 93523	1
Dr. F. Roberto Code AFRPL MKPA Edwards AFB, CA 93523	1
Dr. L.H. Caveny Air Force Office of Scientific Research Directorate of Aerospace Sciences Bolling Air Force Base Washington, D.C. 20332	1
Mr. Donald L. Ball Air Force Office of Scientific Research Directorate of Chemical Sciences Bolling Air Force Base Washington, D.C. 20332	1
Dr. John S. Wilkes, Jr. FJSRL/NC USAF Academy, CO 80840	1
Dr. R.L. Lou Aerojet Strategic Propulsion Co. P.O. Box 15699C Sacramento, CA 95813	1
Dr. V.J. Keenan Anal-Syn Lab Inc. P.O. Box 547 Paoli, PA 19301	1
Dr. Philip Howe Army Ballistic Research Labs ARRADCOM Code DRDAR-BLT Aberdeen Proving Ground, MD 21005	1
Mr. L.A. Watermeier Army Ballistic Research Labs ARRADCOM Code DRDAR-BLI Aberdeen Proving Ground, MD 21005	1
Dr. W.W. Wharton Attn: DRSMI-RKL Commander U.S. Army Missile Command Redstone Arsenal, AL 35898	1